FINAL REPORT

SERDP/Office of Naval Research Workshop on Acoustic Detection and Classification of UXO in the Underwater Environment

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ACRONYMS

APL-UW	Applied Physics Laboratory, University of Washington
ATG	Air-to-Ground
ATR	Automated Target Recognition
AUC	Area-Under-the-Curve
AUV	Autonomous Underwater Vehicle
BUD	Berkeley Unexploded Ordnance Discriminator
BOSS	Buried Object Scanning Sonar
BRAC	Base Realignment and Closure
CAD/CAC	Computer Aided Detection and Classification
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CMRE	Centre for Maritime Research and Experimentation
CSAS	Circular Synthetic Aperture Sonar
DOD	Department of Defense
EM(I)	Electromagnetic (Induction)
EOD	Explosive Ordnance Disposal
ER,N	Environmental Response, Navy
ESTCP	Environmental Security Technology Certification Program
FE(M)	Finite Element Model
FSNSD	Former Seattle Naval Supply Depot
FUDS	Formerly Used Defense Sites
FWG	Forschungsanstalt der Bundesweha fur Wasserschall und Geophysik (Federal Armed Services Underwater Acoustics and Marine Geophysics Research Institute in Kiel Germany)
HLS	Heat, Light, and Sound Research, Inc.
iSSAM	Intersection in Signal Processing, Acoustic, and ATR for Maritime applications (an ONR workshop)
LIA	Live Impact Area
LSG	Laser Scalar Gradiometer

PMA	Production and Manufacturing Area
MBUD	Marine version of BUD
MC	Munitions Constituents
MCM	Mine Countermeasures
MEC	Munitions and Explosives of Concern
MLLW	Mean Lower Low Water
MR	Munitions Response
MRP	Munitions Response Program
MRS	Munitions Response Site
MTA	Marine Towed Array
MUDSS	Mobile Underwater Debris Survey System
NAS	Naval Air Station
NAVFAC	Naval Facilities Engineering Command
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NSWC-PCD	Naval Surface Warfare Center Panama City Division
ONR	Office of Naval Research
Pd	Probability of Detection
REMUS	Remote Environmental Monitoring Units
ROC	Receiver Operating Characteristic
ROV	Remotely Operated Vehicle
RTG	Real-time Tracking Gradiometer
RVM	Relevance Vector Machine
SAS	Synthetic Aperture Sonar
SSA	South Shore Area
SSAM	Small Synthetic Aperture Minehunter
SERDP	Strategic Environmental Research and Development Program
SON	Statement of Need
TNO	Netherlands Organisation for Applied Scientific Research

USACE	U.S. Army Corps of Engineers
UXO	Unexploded Ordnance
VNTR	Vieques Naval Training Range
WSU	Washington State University

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The Strategic Environmental Research and Development Program (SERDP) hosted a workshop on "Acoustic Detection and Classification of Unexploded Ordnance (UXO) in the Underwater Environment" on 16-17 July, 2013, at the Fort Myer Community Center in Arlington, Virginia. The purpose of the workshop was to evaluate the progress made in development of acoustic techniques to detect and classify UXO in the underwater environment and to outline a path for future research. The 38 workshop attendees represented 20 institutions and six countries. Their participation in this workshop is greatly appreciated.

The strategy for achieving the workshop objectives was developed by the workshop coordinating committee: Herb Nelson (SERDP), Mike Richardson (Institute for Defense Analyses and SERDP), Kevin Williams (Applied Physics Laboratory, University of Washington), Bryan Harre and Steve Hurff (Naval Facilities Engineering Command), and Jason Stack and Kyle Becker (Office of Naval Research). This report was written and compiled by the members of the organizing committee along with Dan Sternlicht (Naval Surface Warfare Center, Panama City Division), Larry Mayer (Center for Coastal and Ocean Mapping, University of New Hampshire), and Andrew Schwartz (U.S. Army Corps of Engineers).

We would also like to thank Jamey Westerman at Fort Myer Community Center for the excellent facilities and cooperation in hosting the workshop. Much of the organization of the workshop, development of the website, and formatting of the workshop report was done by Daniel Ruedy of HydroGeoLogic, Inc. This workshop was supported by SERDP, Dr. Anne Andrews, Acting Director.

EXECUTIVE SUMMARY

The Strategic Environmental Research and Development Program (SERDP) hosted a workshop on "Acoustic Detection and Classification of Unexploded Ordnance (UXO) in the Underwater Environment" on 16-17 July, 2013, at the Fort Myer Community Center in Arlington, Virginia. The purpose of the workshop was to evaluate the progress made in development of acoustic techniques to detect and classify UXO in the underwater environment and to outline a path for future research. The 38 workshop attendees represented 20 institutions and six countries. Program managers, research scientists, system developers, and remediation managers were in attendance.

The workshop began with introductory presentations and white papers on previous and current UXO remediation and mine clearance work supported by SERDP, the Environmental Security Technology Certification Program (ESTCP) and the Office of Naval Research (ONR). This included a summary of the highly successful SERDP/ESTCP Munitions Response detection, classification, and remediation research program, the past and present Munitions Response underwater research program, and ONR's mine detection and classification programs. This was followed by presentations on the inventory of underwater Munitions Response sites and a description of the Department of Defense's (DOD) munitions response program. The last two presentations included a review of the science and technology of high- and low-frequency acoustic detection and classification, research needs, and future possibilities. Breakout groups developed perspectives on current state of underwater UXO research, directions for the future, and future system requirements.

This report summarizes the introductory presentations and discussions. We include details on some example underwater munitions sites and a listing of the similarities and differences between UXO detection and classification and mine countermeasures for use by sensor and system developers. Finally, we propose a roadmap for the continued development and demonstration of acoustic sensors and systems for munitions response. Included as appendices to this report are the meeting agenda, a list of participants, a summary of a 2010 SERDP side meeting on acoustics detection and classification of underwater UXO, and underwater acoustic related publications from the SERDP munitions response program.

Acoustic systems have inherent advantages over magnetic and electromagnetic induction (EMI) sensors including much greater areal coverage rates and fewer platform design issues. However, these acoustic systems may not be as effective in water depths less than 3-5 m. In these shallow water environments, magnetic and EMI systems deployed using benthic crawlers or unmanned surface vehicles (USVs) may offer better detection and classification probabilities with roughly the same areal coverage rates. A quantitative analysis of UXO remediation requirements across the full spectrum of Formerly Used Defense Site (FUDS), Base Realignment and Closure (BRAC), and active sites is not available at present. We assume that a sufficient requirement for detection and classification of proud and buried UXO in waters deeper than 3-5 m exists.

Operational and platform requirements may be substantially different between mine clearance and UXO remediation. Therefore, SERDP has a major push to develop acoustic sensors, systems, and platforms that are optimized for the UXO remediation. The level of maturity of high-frequency imaging systems is much greater than for lower-frequency systems that exploit both scattering and structural acoustic properties of UXO. As a consequence, SERDP-supported research should concentrate on these lower-frequency systems that are designed to detect and classify buried UXO. Many of the commercially-available higher-frequency sonar systems may be ready for ESTCP demonstration.

The research emphasis for the lower frequency systems, especially synthetic aperture sonar (SAS), should, for now, remain at the sensor level. Physics-based acoustic research has progressed from conceptual models, laboratory tank testing, pond experiments, to well-controlled field tests. The next experiments should include the deployment of sensors on towed, remotely-operated vehicle (ROV), autonomous underwater vehicle (AUV), or autonomous surface vehicle platforms.

Simulations are required to develop a library of UXO signatures and environments that can be used for template matching and the environmental factors that can influence the matching. Physics-based algorithms should be developed to exploit acoustic color (intensity in frequency and target aspect angle space) plots.

1.0 INTRODUCTION AND OBJECTIVES OF THE WORKSHOP

The Strategic Environmental Research and Development Program (SERDP) hosted a workshop on "Acoustic Detection and Classification of Unexploded Ordnance (UXO) in the Underwater Environment" on 16-17 July, 2013, at the Fort Myer Community Center in Arlington, Virginia. The purpose of the workshop was to evaluate the progress made in development of acoustic techniques to detect and classify UXO in the underwater environment and to outline a path for future research. Topics addressed included both high- and low-acoustic frequencies; imaging techniques and structural acoustic approaches; and focused on detection and classification of proud, partially buried, and fully buried UXO. The strategy for achieving the workshop objectives was developed by the workshop coordinating committee: Herb Nelson (SERDP), Mike Richardson (Institute for Defense Analyses and SERDP), Kevin Williams (Applied Physics Laboratory, University of Washington [APL-UW]), Bryan Harre and Steve Hurff (Naval Facilities Engineering Command [NAVFAC]), and Jason Stack and Kyle Becker (Office of Naval Research [ONR]). The strong presence of ONR program managers and ONR-supported scientists reflect the similar acoustic research issues encountered with mine clearance and UXO remediation. The presence of numerous scientists from Europe demonstrates the international importance of UXO remediation. This report was compiled and written by the members of the organizing committee along with Dan Sternlicht (Naval Surface Warfare Center, Panama City Division [NSWC PCD]), Larry Mayer (Center for Coastal and Ocean Mapping, University of New Hampshire), and Andrew Schwartz (U.S. Army Corps of Engineers [USACE]). The workshop agenda is included as Appendix A and a list of attendees is included as Appendix B.

Many active and former military installations have artillery and bombing ranges and training areas that include adjacent water environments such as ponds, lakes, rivers, estuaries, and coastal ocean areas. At other sites, training and testing areas were deliberately situated in water environments. Disposal and accidents have also generated munitions contamination in the coastal and inland waters throughout the United States. The USACE has identified more than 400 underwater Formerly Used Defense Sites (FUDS) that are potentially contaminated with munitions. The Navy Munitions Response Program (MRP) currently has an additional 57 closed (i.e., Base Realignment and Closure [BRAC]) and active (i.e., Environmental Response, Navy [ER,N]) sites potentially contaminated with munitions. These areas are in shallow water (0-120 feet) where the munitions can pose a threat to human health and the environment. Some of these sites date back to the 18th century and others were used as recently as this decade. Current areal estimates of munitions in underwater environments exceed 10 million acres. Deeper water areas are known to contain munitions from disposal activities that took place through the early 1970s. Munitions may migrate in the underwater environment and it is not uncommon for munitions to wash onshore during storm events. Dredging projects frequently encounter munitions. Both the USACE and the Navy's Munitions Response Program (through NAVFAC) are charged with managing the remediation of these underwater UXO and require the best technologies to detect, classify, and remediate these munitions.

SERDP and ESTCP's Munitions Response (MR) program supports the development and demonstration of innovative technologies that can characterize, remediate, and manage sites affected by military munitions found at terrestrial and underwater sites (http://www.serdp.org/Program-Areas/Munitions-Response). SERDP's success in development of advanced terrestrial UXO electromagnetic classification systems potentially reduces the need to excavate 70% of detected clutter on terrestrial sites thus greatly reducing the potential remediation costs (which allows more area to be cleaned with fixed budgets) and lessening the environmental impact of the remediation. The land-based UXO munitions remediation program currently supports live site demonstrations of these advanced technologies through funding from ESTCP. The emphasis of the SERDP Munitions Response program has therefore shifted to the very challenging underwater environment. Is there a similar "silver bullet" that can greatly reduce the costs of underwater UXO remediation? Of the 72 current and past underwater munitions (MR) projects supported by SERDP/ESTCP, **28 are related to acoustic detection and classification,** 27 are related to electromagnetic induction (EMI) or magnetic detection and classification, eight are related to UXO migration or burial, five to optical detection and classification, five to in situ remediation, two to remediation management and performance models, and three to platforms. Most of these projects were conceived after the "SERDP and ESTCP Workshop on Technology Needs for the Characterization, Management, and Remediation of Military Munitions in Underwater Environment" held in October 2007 (http://www.serdp.org/Program-Areas/Munitions-Response/Underwater-Environments). The 2013 workshop was restricted to the evaluation of progress made in development of acoustic techniques to detect and classify UXO in the underwater environment and to outline a path for future direction. Future workshops will be devoted to electromagnetic and magnetic detection and classification of UXO and UXO migration and burial.

The 2013 workshop began with introductory presentations and white papers (see Appendix A) on previous and current UXO remediation and mine clearance work supported by SERDP, ESTCP, and ONR. This included a summary of the highly successful SERDP/ESTCP land-based remediation program, the past and present Munitions Response underwater research program, and ONR's mine detection and classification programs. This was followed by presentations on the inventory of underwater UXO remediation sites and a description of the Congressional mandated UXO munitions response program. The last two presentations included a review the science and technology of high- and low-frequency acoustic detection and classification, research needs, and future possibilities. Breakout groups developed perspectives on the current state of underwater UXO research, directions for the future, and future system requirements. This report summarizes the results of the workshop, provides direction for future acoustic remediation efforts, and can be used as a guide for future proposals.

2.0 SUMMARY OF PROGESS OF THE SERDP/ESTCP UNDERWATER MUNITIONS RESPONSE PROGRAM

Most of the underwater munitions response (MR) projects supported by SERDP/ESTCP are related to acoustic, optical, magnetic, and electromagnetic detection and classification of UXO. A more recent emphasis has been directed toward the prediction of UXO burial, migration, and re-emergence. Some earlier projects investigated methods of in situ remediation and underwater platforms. A description of all past and current underwater munitions response (MR) projects including links to interim and final project reports can be found at (http://www.serdp.org/Program-Areas/Munitions-Response/Underwater-Environments). All but the first 10-12 of these projects were influenced by the ***SERDP and ESTCP Workshop on Technology Needs for the Characterization, Management, and Remediation of Military Munitions in Underwater Environments.*** The final report from that workshop recommended 10 areas of overarching issues and technology requirements that had the highest priority for future SERDP research and ESTCP demonstrations. These include:

1. Develop a comprehensive inventory of munitions response sites in the underwater environment.
2. Establish test beds for evaluation of sensor technologies.
3. Evaluate munitions mobility in the underwater environment.
4. Characterize the acoustic response of munitions and typical bottom clutter.
5. Combine existing sensor and navigation technologies.
6. Investigate the role of chemical and laser line scan sensors.
7. Explore munitions indicators that can be exploited for wide area surveys.
8. Improve detection of smaller munitions items by electromagnetic (EM) and magnetic systems.
9. Conduct navigational error analysis.
10. Improve methods for discrimination and classification.

Recent SERDP/ESTCP Statements of Need (SONs) have emphasized development of sensors that can detect and classify buried UXO (areas 4, 6, 8, and 10) which are relevant to wide area and detailed UXO surveys. It is felt that issues associated with underwater platforms (areas 5 and 9) and the establishment of test beds (area 2) would follow sensor development. Prediction of UXO burial, migration, and re-emergence (area 3) supports the development of sensor performance models and UXO risk analyses. It is felt that development of a comprehensive inventory of munitions response sites (area 1) is not a research issue (see section 5). Research supporting the exploitation of munitions indicators (area 7) has not specifically been supported but is related to the development of sensors and sensor systems. In this section we will describe the progress SERDP/ESTCP researchers have made in the areas listed above.

Test Beds: Project-specific test beds have been established to evaluate acoustic, magnetic, electromagnetic, and optical sensor designs and demonstrate commercial and military systems. However, no consistent set of test bed requirements have been established similar to those associated with terrestrial UXO remediation demonstrations. Underwater navigation issues, inadequate ground truth for the types and location of UXO, lack of test evaluation strips, and lack of environmental ground truth have all hampered the evaluation of sensors and sensor systems used to detect and classify underwater UXO. A sidebar meeting held at the 2011 SERDP Symposium established the following underwater test bed requirements. A mobile, re-deployable test bed concept is preferable and more cost effective than permanent single or multiple test beds. The location, orientation, and depth of UXO and clutter should be well known. Environmental conditions that affect the operational effectiveness of acoustic, optical, magnetic, and electromagnetic detection and classification sensor systems are time dependent and should be characterized before, during, and after experiments or demonstrations. These include at a minimum: sediment type, bathymetry, water clarity, hydrodynamic conditions (waves and currents), and clutter. The test beds should provide a consistent, quantifiable set of conditions to allow comparison between sensors and sensor systems during individual experiments and between the results of experiments conducted at different sites and at different times. Deployment and maintenance of such a mobile, re-deployable test bed should be led by a team not associated with the UXO detection and classification sensor systems that are being evaluated.

UXO Burial and Mobility: Because of its obvious importance, research related to UXO burial, mobility, and re-exposure has recently become a priority for SERDP/ESTCP. In contrast to terrestrial sites, the underwater environment is dynamic and UXO often do not stay in place. That greatly complicates risk assessment, detection and classification, and subsequent remediation efforts. The burial state also complicates prediction of UXO corrosion and the fate and transport of explosive and chemical contaminants. UXO burial and migration models include physics-based impact and scour models, engineering type empirically-driven models, and probabilistic Bayesian network models (so-called expert system). These models, many developed under ONR's Mine Burial Program, are being modified and validated for the variety of UXO types and environments of importance for UXO remediation. Ongoing SERDP projects include laboratory and field experiments, development and validation of burial, migration, and re-emergence models, and an integration of these models with in situ sediment characterization from acoustic measurements, historical sediment databases and hydrodynamic databases, and models. The goal is development of probabilistic models that can predict both the short- and long-term behavior and resultant distribution of UXO at underwater remediation sites.

Acoustic Sensors and Systems: SERDP has supported development and/or evaluation of three classes of acoustic sensors: commercial systems, bottom mine detection systems designed for naval applications, and wide band synthetic aperture sensors well-suited for UXO detection and classification. Demonstrations of commercial systems (MHz imaging, kHz side scan imaging, narrow and wideband subbottom profilers, multibeam bathymetric sonar, and high- and low-frequency synthetic aperture sonar [SAS] systems) have been only partially successful. Most of the commercial sonar systems demonstrated to date are high frequency and can only be used for detection of proud targets. The lower-frequency commercial systems that are capable of detecting buried targets are used primarily for imaging. Sonar systems designed for detection and classification of naval mines have been developed for military applications. These sonar systems, deployed on autonomous vehicles and actively navigated towfish, include various versions of the

Buried Object Scanning Sonar (BOSS), a scanning synthetic aperture system capable of imaging buried targets; side scan imaging sonar systems; very high frequency imaging sonar systems; and high- and low-frequency SAS systems. Automated target recognition (ATR) methods are being developed for systems like BOSS based on data collected in laboratory tanks, outdoor facilities, and in highly controlled field experiments. These data are being supplemented by acoustic simulations. Operational and platform requirements are potentially much different between mine clearance and detection and classification of munitions (see section 5). Therefore, SERDP has a major push to develop acoustic sensors, systems, and platforms that are optimized for the UXO remediation. Characterizing the acoustic response of munitions in underwater environments is an essential first step. The signatures of munitions vary depending upon 1) munitions type and size; 2) if it is fully intact; distorted, or broken into munitions-related scrap; 3) internal structure; and 4) if it is buried, partially buried, or proud. Research emphasis has centered on wideband synthetic aperture sonar technology at steep grazing angles (above critical) where the full spectrum of frequency and target aspect angles is used to develop acoustic color plots (e.g., BOSS). These acoustic color plots include a target response from higher-frequency scattering (primarily sensitive to target shape) and lower-frequency structural acoustics. SERDP has supported a progressive range of research starting with modeling and basic tank tests with closely controlled variables. This research has suggested that sufficient information is available in acoustic color plots to supplement the classification process for buried UXO. These experiments have been followed by controlled open water data experiments with a variety of UXO and clutter targets to validate these conclusions and develop a library of UXO acoustic signatures. Simulations are also being run to provide a physical understanding of the target signatures; expand the library of acoustic signatures over the acoustic, target, environmental target space; and provide data to develop UXO detection and classification algorithms. It is anticipated that these controlled experiments will be followed by experiments using surface towed or remote underwater vehicles.

Combine Existing Sensor and Navigation Technologies: Prototype MCM mine detection systems, developed with support from ONR and NSWC PCD, have been tested to determine if they would be effective in detection of proud and buried UXO typically found in the marine environment. These systems include the Mobile Underwater Debris Survey System (MUDSS) and Small Synthetic Aperture Minehunter (SSAMI and II). Sensors included various versions of BOSS, optical systems, active and passive EM sensors, including a passive fluxgate magnetic sensor, the Real-time Tracking Gradiometer (RTG), laser scalar gradiometer (LSG) and an active EM GEM-3 array. The BOSS synthetic aperture system was the most successful in imaging buried objects in coarse bottom sand, and with the most recent version and advanced signal processing is able to detect larger buried UXO and provide general size and shape information for buried UXO. Optical systems were limited by water clarity and were only able to detect proud targets. Navigation issues and poor ground truth limited evaluation of data fusion approaches to UXO classification. Several projects have investigated (both field studies and theoretical modeling) the combined use of magnetic and electromagnetic sensors typically used in terrestrial studies. The most successful of these, the Marine Towed Array (MTA), comprised a towed wing containing eight cesium vapor total field magnetometers and an array of EM61 EMI sensors. A number of surveys were successfully completed using the magnetometers, but reliability problems plagued the EMI sensors, negating their usefulness. However, as a class, these towed systems typically suffered interference from platform and environmental noise, navigation uncertainties, and differences in detection distances (the fall-off rate of signals from

EMI systems is much greater than for magnetic systems). It was the conclusion of both the acoustics and geophysical working groups during sidebar meetings at the 2010 SERDP/ESTCP Symposium, that although detection/classification systems that combine acoustics, passive magnetics, active EMI, and possibly optics may be needed, research and demonstrations on individual systems should take precedence. The capabilities of each sensor type need to be understood and optimized before combining modalities. It is quite possible that optimal acoustic, magnetic, EMI, and optical sensor designs may not be operationally compatible on the same platform.

Optics-Related Sensors and Systems: SERDP/ESTCP has supported demonstrations of optical systems, including video cameras and laser line scanners, with very limited success. This lack of success does not mean optical sensors will not be part of the sensor tool kit used for UXO remediation. The development of full three-dimensional (3-D) mapping and mosaicing of video images combined with ATR algorithms may provide a valuable tool for UXO detection and classification in areas where UXO are proud and the water visibility is good. These tend to be shallow water areas with high recreation potential such as coral reefs.

Electromagnetic (EM) and Magnetic Systems: Current underwater geophysical surveys for UXO are primarily limited to passive magnetic arrays towed from surface vessels or part of integrated multi-sensor remotely-operated vehicles (ROVs). These systems have been shown to detect larger UXO and along with accurate positioning data provide seafloor magnetic contour maps. Some systems such as the MTA have demonstrated the capability of providing accurate data inversions yielding target parameters, including location, size, and depth but accurate classification has not been reported. The biggest issues are stand-off distances (1-2 m from the seafloor for magnetics and preferably closer for EMI), navigation, and noise from the platform. Most of the demonstrations of these passive magnetic systems have lacked the adequate ground truth to evaluate system performance. Active EMI systems similar to the advanced EMI systems used at terrestrial sites are still in the development stages. The differences between land-based and marine systems have not been exploited or fully understood. Modeling and simulations suggest that for EMI sensors, which operate from 100 μs (10 kHz) to 25 ms (40 Hz), seawater has negligible effects on the performance of these next-generation EMI sensors and advanced EMI classification models. SERDP is currently supporting fundamental research and modeling needed to understand the physics of geophysical sensing (electromagnetic, magnetic, and electrical) in the marine environment. These include the effects of a conductive media (seawater) on sensor performance, signal interactions with sea surface and seafloor, and platform interference. These all affect optimal sensor array configurations, maximum stand-off (detection) distances, navigation requirements, platform stability requirements, and ultimately the effectiveness of advanced classification modeling. Based on experimental data and modeling, EMI technology will probably be restricted to cued classification of UXO; whereas magnetic sensors may be used for wide-area and detailed surveys. SERDP is currently supporting the development and evaluation of prototype marine versions of advanced EMI sensor systems such as the 2x2 MetalMapper, a sled version of BUD (MBUD), a frequency-domain digital EMI array mounted on a commercial mid-sized ROV, and a EMI sensor based on both electric (E) and magnetic (B) field sources. SERDP is also supporting the development of a new underwater handheld metal detector based on an array of low-power, miniature, total-field atomic magnetometers.

In Situ Remediation: One of the last phases of UXO remediation is the removal of UXO threats from the environment. The standard method is to use explosives trained divers. This is both dangerous and a costly method of UXO remediation. ESTCP has supported demonstrations of other methods to remediate UXO with limited success. These include generation of bubble curtains to reduce the pressure effects of UXO blow-in-place, wide-mesh screen to capture UXO during dredging operations, and collection of buried UXO using a coffer dam with a large electromagnet.   SERDP is currently supporting a co-robotic (human operator in partnership with a robot) manipulator for the removal of underwater UXO using a ROV.

3.0 STATE OF THE ART: UNDERWATER ACOUSTICS DETECTION AND CLASSIFICATION OF UXO

The last two presentations of Day 1 of the 2013 SERDP workshop included a review of the science and technology of high- and low-frequency acoustic detection and classification. Topics included data acquisition, modeling, signal processing, and target classification. ONR supported a similar workshop directed towards MCM applications in December 2012 (International Workshop on Intersection in Signal processing, Acoustics, and ATR for Maritime applications [iSAAM]).

The two breakout groups from this workshop developed perspectives on the current state of underwater UXO research, directions for the future, and future system requirements. In this section we provide a summary of discussions from those breakout groups related to the state of the art for underwater detection and classification of UXO. The emphasis for the high-frequency acoustic systems is imaging targets and the seafloor; whereas the emphasis for the low-frequency acoustic systems is detection and classification of buried targets. The low-frequency sonar systems take advantage of both shape-related backscattering and structural acoustic responses of UXO. We purposely did not define what is meant by high, mid, and low frequency, allowing some overlap in the breakout group discussions.

3.1 Mid- to High-Frequency Acoustics (Image based detection/classification)

The current state-of-the-art for acoustic imaging systems is summarized in Table 3-1, which includes a mix of commercial off-the-shelf systems and prototype MCM systems designed and optimized for mine clearance. The Buried Object Scanning Sonar (BOSS), originally developed by Dr. Steve Schock, is a SAS system that can image proud, partially buried, and larger buried mines and UXO. The naval versions of BOSS have been demonstrated for UXO wide area surveys by NSWC-PCD and are part of a suite of sensors deployed with AUVs, such as Bluefin 12 and REMUS-600. There are multiple versions of BOSS that vary with frequency and bandwidth, and number, orientation, and spacing of receivers. BOSS has shown considerable success in detection of proud and buried UXO and can provide information on size, shape, depth, and orientation of larger UXO. Development of higher resolution, 3-D versions of BOSS, and the development of circular synthetic aperture sonar (CSAS) image processing show great promise for classification of larger buried UXO and detection and possibility classification of smaller UXO. Research issues include those related to navigation, platform stability, multipath in shallow water, multi-element design, multi-aspect data collection, signal processing, and target classification (automated target recognition in MCM). It is important to optimize the SAS design, signal processing, and target detection and classification algorithms with platform characteristics and operational requirements. As a rule of thumb, detection resolution requires a minimum of 3x3 pixels on the target and classification requires at least 9x9 pixels on target.

A number of very high-frequency sector scan imaging sonar systems are commercially available. These systems have resolutions that approach that of optical systems and are capable of detecting and classifying UXO that are proud or perhaps partly buried. Side scan and multibeam sonar systems designed for seafloor visualization, classification, and bathymetric surveys are also widely available and may be useful for UXO wide area surveys. Commercial single beam subbottom profiling sonar systems are ubiquitous and can, depending on frequency, be used for geophysical studies, sediment classification, and navigation. Because of their narrow track width and low-resolution, these types of single beam systems will play a very limited role in UXO remediation. Low-frequency parametric sonar systems may have a role in the detection of larger, deeply buried UXO. Steerable parametric sonar systems have demonstrated the capability to detect buried pipelines and cables with diameters as small as 3 cm to depths up to 5 m. Swath widths up to 10° are possible.

SERDP is currently supporting the development of physics-based algorithms for sediment classification from high-frequency (150-450 kHz) multibeam sonar systems (Reson Seabat 7125). If successful, these sonar systems should be able to provide sediment characterization needed for UXO wide area surveys. These high-resolution, wide-track width data should be far superior to the single beam downward-looking acoustic sediment classification systems commercially available.

Table 3-1. High Frequency – State of the Art

Detection Resolution Requirements: 3x3 pixels on targets					Classification Resolution Requirements: 9x9 pixels on targets			
Categorizing State of the Art in Acoustic Sensing								
Scan Mode	**Sonar System (e.g)**	**Op. Freq. Range**	**Resol.**	**Op.Alt. (m)**	**Swath Width**	**Det. Limits (Burial State)**	**Class. Limits (Obj size)**	**Commercial Examples**
Down-looking (high grazing angle)	Multi-beam (Reson 7125)	400-455kHz	1/2°, e.g. @5m: 5cm x 2cm	>3m	130°	Proud	Medium to Large dependent on range	Blueview, Didson
	Buried Object Scanning Sonar	5-20kHz	>5cm^3	>3m	15m	Proud/Buried	Buried Medium	EdgeTech
	Parametric (INNOMAR SES-2000)	5-80kHz	1°	>3m	-	Proud/Buried	Buried Large	DRUMS (Guigne International)
Side-looking (low grazing angle)	Mid-freq SAS	>10kHz	5cm x 5cm	>5m	>100m	Proud/Buried	Med. Objects	
	High-freq SAS	>60kHz	2cm x 2cm	>5m	>100m	Proud	Small Obj.	Kongsberg HISAS, AST PROSAS
	High-freq SSS (Klein 5000)	600kHz	Range dependent	>3m	>100m	Proud	Small to Large dependent on range	Edgetech
Notes	Most sensor types mountable across multiple platform types (ship hull/boom, towfish, self-propelled vehicle). High-frequency SAS requires high platform stability. Parametric sonars can require significant power for operation. Classification performance improves with the addition of orthogonal sensors: Magnetic Gradiometer, Camera, or Electro-Optics. Potential operational cost savings using ATR (PMA or embedded) and advanced autonomy.							

3.2 Low- to Mid-Frequency Acoustics (Structural acoustics based detection/classification)

Use of structural acoustic response to detect and classify mines and UXO is a relatively recent effort as compared to acoustic imaging. The advantage from a detection standpoint is that the lower frequencies used result in increased penetration into the sediment above the critical angle, thus providing an increased ability to detect and classify buried objects.

3.2.1 Data Acquisition Efforts in the United States

There have been efforts by NSWC, NRL, and APL-UW to collect data on proud, partially buried, and buried UXO under well-controlled conditions. These controlled data acquisition efforts have been carried out in test pools and ponds that have sand sediment on the bottom. The references given in the modeling section below include data/model comparisons using some of this data. These same groups have moved recently to ocean experiments. The sediment at the location of the recent ocean experiments is sand. Ocean experiments currently planned for Fiscal Year 2014 will be carried out in muddy sediment.

Some of the data taken by NSWC and APL-UW in a large test pond using rail-mounted sensors is available as public release. Inquiries can be made to the SERDP office directly for copies of these data (see section 9 for more details). The data includes scattered returns from several UXO and natural items at a large number of look angles.

3.2.2 Data Acquisition Efforts in Europe

Data acquisition efforts by the Netherlands Organisation for Applied Scientific Research (TNO), Federal Armed Services Underwater Acoustics and Marine Geophysics Research Institute (FWG), and Centre for Maritime Research and Experimentation (CMRE) in ocean/harbor environments have begun, with several new efforts being anticipated in the next few years. TNO is working in collaboration with the European Defense Agency. They will be fielding their low frequency acoustic system as well as a magnetometer as part of that collaborative effort; a joint sea trial is anticipated in 2015. They have already acquired data using a hull mounted low-frequency system and have shown success in detecting objects in muddy sediments. FWG has been testing a variety of acoustic systems, including low-frequency systems, and are anticipating the first sea trials in October 2013. They will be joining with CMRE as part of a Joint Research Program in the next few years. Part of the FWG strategy is to compare different systems to decide site-specific optimal sensors and combinations of sensors. CMRE efforts have been aimed primarily at MCM systems and have focused on assuring UUV utilization of the MCM sensors to be fielded. CMRE now has a rail system in operation in a shallow water ocean environment with a silt bottom.

3.2.3 Modeling - United States

Combinations of FE and various propagation models have been developed that have high fidelity when compared to results from controlled experiments. At this point, all models use a combination of FE methods to handle scattering in the near vicinity of the target and then various propagation models to determine scattered pressure at the location of the receivers. NSWC, NRL, and HLS all have modeling capabilities developed entirely within the United States. Results from these models have been compared to data (Ref. 1-3) and used in classification studies (Ref. 3)

3.2.4 Modeling – United States/Europe collaboration

APL-UW, Washington State University (WSU), and TNO have been collaborating on model development with a similar philosophy to the U.S.-only efforts, i.e, combining FE modeling local to the target with various physical acoustics models to handle propagation to the receiver (Ref. 1,2,4-6). APL-UW has developed a propagation modeling technique (Ref. 4) that can be combined with FE results and increase the overall computation speeds by a factor of 1000 with small loss in fidelity compared to test pond data, at least from one simple metric of probability of correct classification using template matching. The fidelity of these modeling techniques, as well as those of the previous section, relative to this and other metrics needs to be quantified using ocean data.

3.2.5 Signal Processing

A technique to isolate individual targets using initial SAS processing has been developed (Ref. 7). Using this technique, the acoustic response of targets with cross range separations as little as 1 m can be recovered. The data from test pond experiments (Section 3.2.1) have been used individually and summed to examine the classification characteristics of simple relevance vector machine classification schemes using acoustic template matching. These studies have produced ROC curves with Area-Under-the-Curve (AUC) of about 0.84 using experimentally derived templates and 0.8 using model templates. Alternative RVM analyses using data acquired in a test pool have also shown the model-derived scattering to be of sufficient fidelity to allow classification (Ref. 3). Carrying out similar studies using ocean data is the next step.

Finding better ways to use the acoustic response in classification (e.g., finding and using robust features derived from the acoustic templates) is a current area of research. Incorporating this information into ATR algorithms should increase efficiency of detection/classification efforts.

3.2.6 Summary/Discussion

Workshop participants identified several topics that need to be addressed next based on the current state of the art:

- What are the tradeoffs of speed/fidelity, and how much fidelity is enough? We have not identified the metrics needed to answer this.
- For acoustic color, the predominant classification technique is template matching.
    - Is template matching good enough, the best, or appropriate?
    - Is template matching not the operational answer, but good enough to ask the experimental questions?
    - If it is, how to generate the libraries / templates that can take into account a wide range of variations of parameters and geometries?
- How to extract useful features from acoustic color data?
- Need to explore the regions where elastic sediment modeling might be required

There was significant discussion of the similarities and differences of the MCM and UXO problem. A summary of much of that discussion can be found in section 6 below. One important point from these discussions is that the sensors being used and the classification schemes used on the resulting data will have considerable overlap even if the systems on which the sensors are deployed may be different. Thus, leveraging MCM and UXO similarities in this regard will continue to be a benefit to both.

4.0 THE WAY AHEAD AND PROPOSED TIMELINE

The SERDP munitions response (MR) program has supported 28 projects related to acoustic detection and classification of UXO in the underwater environment. Much of the current portfolio is directed towards detection and classification of buried UXO using lower-frequency (1-50 kHz) SAS. Given that over 70% of UXO (Ref. 9) are probably buried this seems like a wise decision. Acoustic systems have inherent advantages over magnetic and electro-magnetic induction sensors including much greater areal coverage rates and fewer platform design issues. However, these acoustic systems may not be as effective in water depths less than 3-5 m. In these shallow water environments, magnetic and EMI systems deployed using benthic crawlers may offer better detection and classification probabilities with roughly the same areal coverage rates. In spite of the detailed description of UXO remediation efforts at four sites, given in the next section, a quantitative analysis of UXO remediation requirements across the full spectrum of FUDS, BRAC, and active sites is not available. At present, we will assume that a sufficient requirement for detection and classification of proud and buried UXO waters deeper than 3-5 m exists.

Operational and platform requirements may be substantially different between mine clearance and UXO remediation (see section 5). Therefore, SERDP has a major push to develop acoustic sensors, systems, and platforms that are optimized for the UXO remediation. Based on group discussion the level of maturity of high-frequency imaging systems is much greater than for lower frequency systems that exploit both shape-related scattering and structural acoustic properties of UXO. As a consequence, SERDP supported research should concentrate on these lower frequency systems which are designed to detect and classify buried UXO. Many of the commercially-available, higher-frequency sonar systems may be ready for ESTCP demonstration.

The hardware and signal processing for high-frequency imaging sonar systems, such as side-scan, sector scanning, and multibeam sonar systems is well developed and probably more than adequate for UXO remediation. The research emphasis for these systems should be directed towards detection and classification algorithms. This includes the effects of the environment on target scattering, signal processing and classification. The use of calibrated systems for assessing actual target strength should be encouraged. Test beds need to be developed to provide performance predictions for a variety of UXO and environments.

The research emphasis for the lower-frequency systems, especially SAS, should, for now, remain at the sensor level. Physics-based acoustic research has progressed from conceptual models, laboratory tank testing, and pond experiments to well-controlled field tests. This research has suggested that sufficient information is available in acoustic color plots to develop classification algorithms for buried UXO. The controlled open water experiments have been conducted with a variety of UXO and clutter targets to validate these conclusions and develop a library of UXO acoustic signatures. The next experiments should include the deployment of sensors on towed, ROV, or AUV platforms in environments where UXO remediation is required. Simulations are required to develop a library of UXO signatures and environments that can be used for template matching. Physics-based algorithms should be developed to exploit acoustic color (intensity in frequency and target aspect angle space) plots. The next step should be platform/sensor integration, testing in well-developed test beds, and demonstration at live sites. UXO remediation may require that multiple sensor modalities be used at many sites. However, capabilities of each sensor type needs to be understood and optimized before combining modalities. It is quite possible that optimal acoustic, magnetic, EMI, and optical sensor designs may not be operationally compatible on the same platform.

SERDP/ESTCP Underwater Acoustic Munitions Response Roadmap

- Finite element and other simulations to develop acoustic color datasets: 2014, 2015, 2016
- Controlled open water experiments: 2013, 2014
- Open water experiments using mobile platforms: 2014, 2015, 2016
- Development of low-frequency SAS classification algorithms: 2013, 2014, 2015, 2016
- Development of image based classification algorithms: 2014, 2015, and 2016
- Platform/acoustic integration; 2015
- Integration testing: 2016
- Mobile test bed development: 2015, 2016, 2017
- Live site demonstrations: 2017, 2018, etc

5.0 UNDERWATER MUNITIONS RESPONSE SITES

As mentioned in the introduction, most underwater munitions response sites are managed by the Navy and USACE. There are over 450 sites across the United States identified as having potential contamination with underwater munitions. In this section, we present a brief outline of the CERCLA process, list the criteria used by the Navy for including sites in the Munitions Response Program and give examples of four broad classes of sites from both programs.

5.1 Munitions Response and CERCLA

In most cases, munitions response projects are carried out following the CERCLA process. A simplified work flow is shown in Figure 5-1.

PA/SI → RI/FS → ROD → RD/RA → RC

Figure 5-1. The CERCLA process as applied to munitions response

The major steps in this process include:

- Preliminary Assessment/Site Inspection: Investigations of site conditions.
- Remedial Investigation/Feasibility Study: Determines the nature and extent of contamination. Assesses the treatability of site contamination and evaluates the potential performance and cost of treatment technologies.
- Record of Decision: Documents the cleanup alternative chosen for the site.
- Remedial Design/Remedial Action: Preparation and implementation of plans and specifications for applying the remedy.
- Response Complete: The remediation has been completed.

5.2 Current Navy Policy for Inclusion of Underwater Sites into the Navy's MRP

The Navy's MRP addresses response actions at munitions response sites (MRSs). The Navy uses the following criteria for inclusion of water sites into the Munitions Response Program.

Shallow water areas where munitions releases are known or suspected to have occurred and where:

- o Navy actions are responsible for the release
- o The munitions are covered by water no deeper than 120 feet
- o The site is not:
  - ▪ Part of, or associated with, a designated operational range (terrestrial or water range)
  - ▪ A designated water disposal site
  - ▪ A Formerly Used Defense Site
  - ▪ A result of combat operations
  - ▪ A maritime wreck
  - ▪ An artificial reef

The Navy considers munitions located in waters between high and low tides terrestrial

5.3 Examples of Underwater Munitions Response (MR) Areas

Underwater munitions response areas encompass a large variety of conditions and munitions profiles but a number of them fall into several broad categories. Four example areas are detailed below to serve as a guide for developers of sensors, analysis methodologies, and systems.

5.3.1 Former Mare Island Naval Shipyard (Navy)

Mare Island Naval Shipyard was closed as part of the BRAC process. Mare Island Naval Shipyard has four underwater MRSs. The MEC contamination at Mare Island Naval Shipyard is related to the accidental or intentional disposal into the water from Navy piers and along the shoreline. The site descriptions at Mare Island Naval Shipyard are as follows:

Fleet Reserve Piers – These piers were used for storage of the Reserve Fleet post World War II (WWII) on the Napa River. The site has a water depth of up to 30 feet with a silty bottom and low visibility in the water. The site is suspected to have MEC because of the timeframe and potential wartime use.

Berths 2&3 - Berths on the Napa River were used by EOD Mobile Unit 9. The MRS has a water depth of up to 10 m with a silty bottom and low visibility in the water. The MRS is suspected of having MEC because of the adjacent land use by an EOD boat unit.

Ammunition Production and Manufacturing Area (PMA) Offshore/Mare Island Strait – This MRS is an offshore area adjacent to the Ammunition Production and Manufacturing Area (PMA) which includes shallow areas as well as areas as deep as 30 feet. The MRS boundary is from the shoreline to areas around the current and former piers. The Mare Island Strait connects the Napa River to San Pablo Bay and is a low visibility area used by commercial and recreational boat traffic. The MRS is suspected of having MEC because of the land based munitions operations and pier use from the 1850s until the 1990s. Additionally, MEC has been found on the land adjacent to the MRS and at certain locations along the shoreline.

South Shore Area (SSA) Offshore/Carquinez Strait - This site is the offshore area adjacent to the South Shore Area which supported the PMA. It includes the shallow areas as well as areas as deep as 10 m from the shoreline to around the current and former piers. The Carquinez Strait connects the Sacramento River to San Pablo Bay and is a low visibility area used by commercial and recreational boat traffic. The MRS is suspected of having MEC because of the land-based munitions operations and pier use from the 1850s until the 1990s. Additionally, MEC has been found on the land adjacent to the MRS and at certain locations along the shoreline.

5.3.2 Former Vieques Naval Training Range (Navy) & Culebra Water Ranges (USACE)

The former Vieques Naval Training Range (VNTR) is situated in the eastern half of the Island of Vieques, and is bordered on the west by the community of Isabel Segunda, to the north by Vieques Sound, and to the south by the Caribbean Sea. Culebra Island is located approximately 17 miles east of Puerto Rico and approximately 9 miles northeast of Vieques.

The former VNTR consists of approximately 14,500 acres. The Navy has owned portions of Vieques since 1941, when land was purchased for use as an ammunitions storage facility in support of WWII training requirements. Although the island of Culebra was the focal point for naval gunfire in the 1960s and early 1970s, the development of facilities on the eastern end of Vieques was undertaken in 1964, when a gunnery range was established in the live impact area (LIA). The Atlantic Fleet's ships, aircraft, and Marine forces carried out training in all aspects of Naval gunfire support, ATG ordnance delivery, air-to-surface mine delivery, amphibious landings, small-arms fire, artillery and tank fire, and combat engineering. The records indicate there were off-shore munitions hits. The VNTR was closed in 2003 and is now designated the Vieques National Wildlife Refuge. The majority of the area is off limits to the public due to the presence of MEC.

Limited surveys of MEC have been conducted in two offshore areas. The physical areas are Bahia Icacos, and Bahia Salinas. Depths in Bahia Icacos are between 1 and 5 m, and up to 7 m. Fourteen soundings were taken in Bahia Salinas and the deepest portion of the bay (6-7 m) is a narrow channel between two shoal areas. The central portion of the bay is approximately 5 m. The total area going out to 30 m depth limit is approximately 9000 acres.

The National Oceanic and Atmospheric Administration (NOAA) completed an "An Ecological Characterization of the Marine Resources of Vieques, Puerto Rico" in 2010. The following table and text summarizes the bottom types for the entire island of Vieques

Table 5-1. Structures Around Vieques Island

Major Structure	Area (km^2)	Percent Area	Detailed Structure	Area (km^2)	Percent Area
Coral Reef and Hardbottom	119.56	33.44	Rock/Boulder	1.38	0.39
			Aggregate Reef	13.79	3.86
			Individual Patch Reef	6.46	1.81
			Aggregated Patch Reef	1.91	0.54
			Spur and Groove	0.02	0.01
			Pavement	39.37	11.01
			Pavement with Sand Channels	5.98	1.67
			Reef Rubble	17.53	4.90
			Rhodoliths	33.11	9.26
Unconsolidated Sediment	237.95	66.56	Sand	220.39	61.64
			Mud	7.88	2.20
			Sand with Scattered Coral and Rock	9.69	2.71
Other Delineations (land excluded)	0.05	0.01	Artificial	0.05	0.01
Total	**357.56**	**100.00**		**357.56**	**100.00**

The composition and extent of bottom structure and biological cover around Vieques varies over space. The area north-northwest of Vieques is dominated by sand with submerged aquatic vegetation, interspersed by numerous patch reefs. Moving east from Isabel Segunda, a system of shallow Lagoons and Reef Flats extend from shore, bordered seaward by a line of Pavement and Aggregate Reef. A large area of Rhodoliths dominated by algae cover sits offshore in the deeper water. The formation of Pavement and Aggregate Reef extends around the eastern tip of the island to the south side, where it is more extensive than on the north. Two linear systems of Pavement and Aggregate Reef are present on the south coast; one close to shore, while another is further offshore along the shelf edge. The large area lying between these two reef systems southeast of Vieques is a depression approaching 30 m in depth that was primarily mapped as Reef Rubble. Biological cover types include Seagrass, Algae, Mangrove and Coral.

The Department of Defense used the island of Culebra and adjacent islands and cays to train troops for combat and, although DOD ceased activities in the mid-1970s, military munitions remain on the islands and surrounding waters. Of the 13 MRSs on Culebra, at least six have an underwater component.

The water depths and bottom characteristics on Culebra are similar to those on Vieques. For example, in MRS 09 both mud and sand bottoms were observed with sand being the majority and in MRS 13 sand was the predominant cover. In both of these MRSs, areas of colonized and uncolonized hard bottom and coral reef were observed. In MRS 09, depths range from 0 to 20 feet while in MRS 13 the maximum depth is 50 feet.

5.3.3 NAS Patuxent River UXO 0001 (Navy)

NAS Patuxent River is located in St. Mary's County in southern Maryland, approximately 65 miles southeast of Washington, D.C., at the confluence of the Patuxent River and the Chesapeake Bay. The Patuxent River supports naval aviation operations by researching, developing, testing, and evaluating aircraft, aircraft components, and related products.

The Historic Munitions Disposal Area (UXO 0001) is located south of the former seaplane basin known as the Chesapeake Basin along the southeastern base boundary. The seaplane basin was constructed in the Chesapeake Bay in 1942, and consists of northern and southern seawalls. A stream known as Pine Hill Run flows along the southeastern boundary of NAS Patuxent River. Pine Hill Run empties into the Chesapeake Bay.

From approximately 1954 to 1974, NAS Patuxent River personnel discarded a variety of excess munitions, both live and inert, into the Chesapeake Bay. At that time, it was a standard safety practice to dispose of old munitions into open water. This practice was halted at NAS Patuxent River in 1974.

The Historic Munitions Disposal Area includes the known disposal area along the seawalls of the Chesapeake Basin and a former pier that was located on base property a few hundred feet south of the basin, as well as a portion of the privately owned beach south of the installation fence that is part of the Cedar Cove subdivision. The privately owned beach is separated from the NAS Patuxent River to the north by Pine Hill Run, which drains into the Chesapeake Bay. The adjacent residential community, Cedar Cove, has approximately 200 homes. Currently, the beach is used for recreational activities by community residents.

Disposed military munitions were reportedly discarded into the Chesapeake Bay from two locations at NAS Patuxent River:

- Along the seawalls of the former seaplane basin that extend approximately 700 feet into the Chesapeake Bay. Based on the locations where discarded munitions have been recovered during past efforts, the majority of the munitions were discarded inside the seaplane basin.
- A pier, located approximately 350 feet south of the former seaplane basin and extending about 50 feet into the bay, which no longer exists.

Over time, the munitions items disposed into the water were moved by tides and currents and eventually some items started washing up on the shoreline both within and beyond the base boundary near where the items were originally discarded. The primary potential source of concern at the site is MEC resulting from historical disposal operations at NAS Patuxent River immediately to the north. MEC may be present beneath the land surface, on the sediment surface, or in the sediment subsurface.

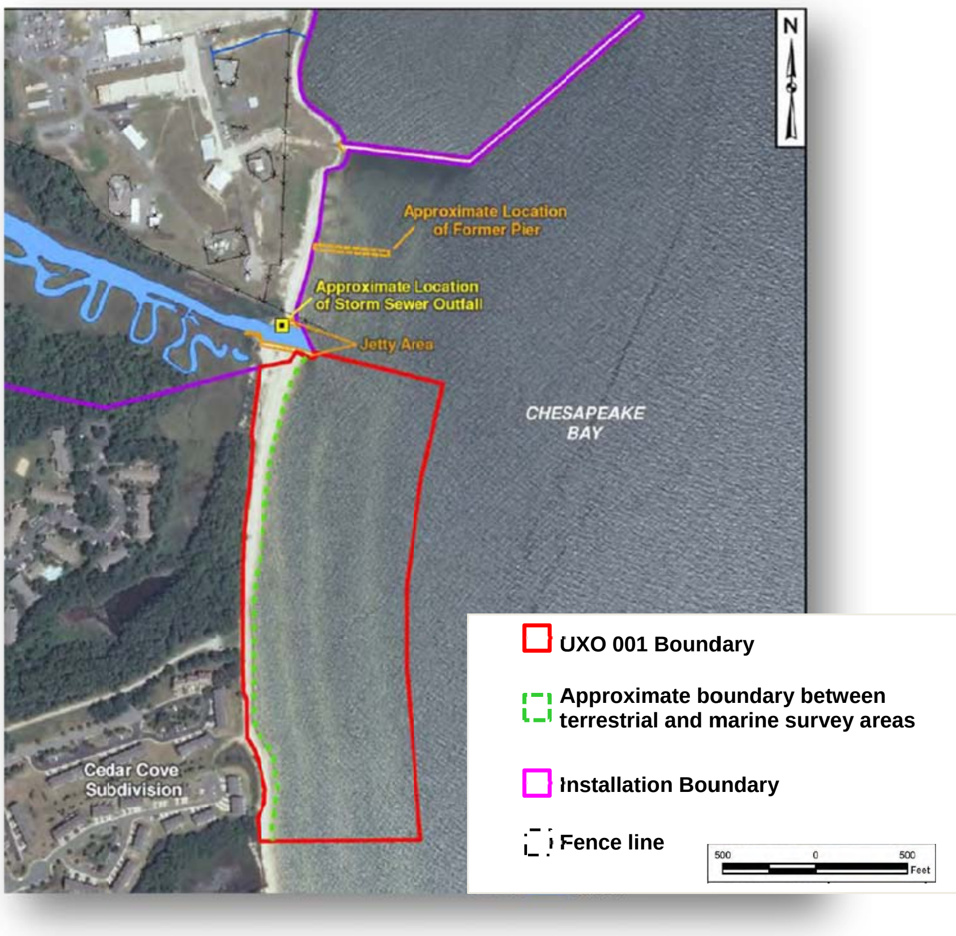

Figure 5-2. NAS Patuxent River

Historic Munitions Disposal Area - It should be noted that most of UXO 0001 has depths of 3 ft or less. The water is turbid, with poor water clarity. This area is also subject to significant erosion due to normal wave and storm actions. One tropical storm removed 2 ft of sand from the beach, resulting in redeposition off-shore. Following these storm events, a number of non-MEC metallic objects have been noted as emerging from the waterfront where they were apparently used as improvised rip-rap or fill. These items appear similar in shape and size to MEC (fence posts/pipes/concrete with rebar). The dynamic nature of the site, coupled with limited sensing depth with magnetometry and EMI makes site investigation challenging.

5.3.4 Former Seattle Naval Supply Depot (USACE)

The former Seattle Naval Supply Depot (FSNSD) is located along the Puget Sound in King County, WA, approximately 3 miles northwest of downtown Seattle at the present day Terminal 91 site. The survey area of interest is classified as being in open water surrounding each of the piers or under the overhang of a pier (approximately 60 ft). These are constructed on fill material connected to an upland area at the north of each pier. The west, south, and east perimeter of each pier includes concrete and treated wood pilings and a supported dock area approximately 80 to 85 ft wide. They are fitted with a combined timber/steel pier fender piling system.

The bathymetry of the FSNSD is diverse going from zero feet Mean Lower Low Water (MLLW) underneath the piers down to greater than 60 ft in the deepest sections of the site. Water depths average 30 feet between the piers and between the Pier 90 and the land. At the end of the piers, there is a steep drop off from 10 feet to greater than 60 feet.

In 1942, and 1943, the U.S. Navy acquired the property through condemnation, which in total consisted of 242.97 acres for use as bulk fuel and material storage, and as a marine terminal for naval vessels to support WWII. It was during this period that Discarded Military Munitions items from naval vessels were deposited on sub tidal areas surrounding the piers. Port of Seattle divers recovered a sign labeled “Safety Orders for 3 Inch Guns” from the seafloor in 2010. One section of the sign instructed sailors to throw potentially damaged or defective 3-inch rounds overboard. Based on the findings it was assumed that sailors jettisoned munitions, and munitions-related items overboard as a housekeeping process and to speed the resupply process. No specific records of these events have been found, and it appears that this was an infrequent occurrence rather than a routine procedure. No evidence suggests that any live fire exercises occurred at the site, and all munitions found to date have been unfired and unarmed.

6.0 OVERLAP BETWEEN UXO AND MCM TECHNOLOGY

The common underwater munitions requirements and research issues between SERDP's underwater Munitions Response program and ONR's Mine Countermeasures, Ocean Acoustics and Littoral Geosciences and Optics programs relate to sensor system design (acoustic, magnetic, electromagnetic, and optical) for target detection and classification including; underwater platform design and navigation, target physics, sediment acoustics, signal processing, data fusion, simulations and modeling, and automated detection and classification. Other common research issues are related to: 1) object (UXO and mines) seafloor-hydrodynamic interactions including burial, migration and reemergence; 2) environmental characterization; and 3) the physical remediation or neutralization of targets. Nowhere is this overlap more obvious than in fields related to the acoustic detection and classification of bottom mines and UXO in the underwater environment. The result has been jointly supported by investigators, modeling and simulations, and laboratory and open ocean experiments. This is especially true for the research issues associated with detection and classification of buried mines and UXO. Acoustic systems designed specifically for mine clearance and a variety of commercial systems have been demonstrated for UXO detection and classification. These acoustic systems include 1) side scan, multibeam, synthetic aperture, high resolution imaging, and parametric sonar systems with frequencies from kHz to MHz; 2) high-frequency imaging to low-frequency systems that exploit imaging and structural acoustics; 3) wide band and single frequency; and 4) wide and narrow beam systems. In spite of this overlap in basic and applied acoustic research issues, there are a number of differences in mine clearance and UXO remediation that must be considered for the final design and operation of UXO systems for wide area and detailed surveys of UXO-contaminated areas. These include the following:

- Success is driven by speed of operations for MCM versus costs of operations and ecological impacts for UXO remediation, human risk is a factor for both but with differing metrics.
- The MCM vision is for a single networked autonomous system including single-pass, real-time detection, classification, identification, and neutralization of mines with automated fusion of data and mission planning. The UXO remediation is a multi-phased, linear, congressionally-mandated legal process that includes preliminary assessment, site inspection, and a remedial investigation/feasibility study leading to a remedial action phase agreed upon by all stakeholders and follow-on, long-term maintenance phase if deemed necessary.
- Mines are cleared for military operations (e.g., operational areas, beach assess). UXO are cleared to provide for civilian safety (e.g., fisheries, diving, cable and pipeline laying, offshore wind farms, port safety).
- Many operational constraints for mine detection, classification, and clearance systems need not apply to UXO remediation systems. These constraints include size, shape, coverage rates, overtness, and autonomy.
- UXO remediation at land sites has been held to an extremely high standard by State and federal regulators. Requirements for probability of detection and classification (P_{dc}) may be much higher for UXO remediation than for MCM Mine clearance.
- Mine clearance (MCM) is sometimes clandestine; whereas, UXO remediation is always a public process.

- MCM operations, results, and data products are sometimes classified. UXO remediation and SERDP research and ESTCP demonstrations must be unclassified.
- MCM operations are conducted by the military; whereas, UXO remediation will predominately be conducted by contractors. The initial costs of UXO detection and classification systems must be included in the overall remediation costs.
- UXO may have been in the environment for many decades before remediation efforts are begun and may be impacted by their environment (corroded, covered in growth, etc). MCM operations are most often conducted on more recently deployed mines.
- UXO are generally magnetic cylinders which are detectable by magnetic and EMI sensors. Mines can be made of non-metallic materials designed to be undetectable by magnetic and EMI sensors. Some mine shapes are designed to deter acoustic detection (stealth).
- UXO are generally cylindrical and range in diameter from 20 mm to 155 mm or greater. Shallow water mines can be small and are often squat cylinders; offshore mines are larger and have a great range of shapes (e.g., larger cylinders, Manta, Rockan).
- Mines have triggers (tactile, acoustic, pressure, magnetic); whereas, most UXO were meant to explode on impact. Mines are inherently more dangerous to military operations and to the public. A cost effective and safe option for underwater UXO remediation may be to leave UXO in place with occasional monitoring if the UXO can be shown to be unlikely to come in contact with the public.
- Mines can be cleared by influence sweeping but influence sweeping will not detonate UXO.
- MCM threats include bottom, moored (in volume, near surface), and freely drifting (surface) mines; whereas, UXO remediation typically concerns only bottom ordnance.
- In MCM, the specific minehunting environments (sites) are not known until the adversary chooses when and where to actually lay the mines.
- MCM detection and classification operations can cause explosions; whereas, UXO detection and classification operations (wide area and detailed surveys) are specifically designed not to cause explosions. Physical remediation of both mines and UXO is hazardous, especially to divers.
- UXO will probably be buried and often biological fouled and chemically corroded more than mines given the longer time left in the environment. The biofouling and corrosion may change the UXO target characteristics with time. UXO (especially smaller UXO) will probably be more mobile than mines in shallow water.
- UXO found in water depths deeper than 120 ft are of lesser interest to SERDP’s MR research program. Deep-water UXO that contain energetic material are not considered a great threat to the public. Mine clearance requirements can extend into waters much deeper than 30 m.
- Large stockpiles of chemical and biological munitions were dumped in deep water prior to 1972, when international treaty restrictions ended that practice. Ecological risk assessments from these munitions are of great national interest but out of the scope of SERDP’s MR or the Navy’s mine warfare programs.

- Higher probability of detection (Pd) requirements for UXO suggest that short range, above critical angle detection acoustic strategies should be emphasized. Longer range below critical angle detection of mines may be required during MCM operations.
- Detection and classification of mines by ATR algorithms are often preferred given the short-term operational requirements. Computer aided detection and classification (CAD/CAC) that includes operators will probably be the norm given the higher P_{dc} requirements and greater time available for UXO remediation.
- Future MCM operations will substantially involve unmanned vehicles (airborne sensors, AUVs, ROVs) whereas UXO detection and classification can be done with towed or hull-mounted sensors or benthic crawlers. The chance of UXO detonation during munitions response is much less than during mine clearance operations.
- Towed or hull-mounted sensors can eliminate much of the navigation uncertainty associated with underwater AUVs and ROVs.

7.0 WHAT KINDS OF SYSTEMS AND PLATFORMS CAN WE EXPECT?

High-frequency acoustic imaging techniques are more advanced compared to lower-frequency techniques that exploit the structural acoustic character of UXO. As such, research advances in these higher frequency systems is more incremental and evolving in character. The numerous applications of high-frequency acoustic imaging systems have led to the commercialization of sensors, platforms and basic signal processing techniques. The main research issues for these high-frequency imaging systems relate to the development of robust classification and identification algorithms. The effects of the environment of target physics (scattering), signal processing, and classification need to be understood. As many as 70% of intact UXO in the underwater environment are buried. Therefore low-frequency acoustic systems, that are less attenuated, are being developed for detection and classification of these buried UXO. Low-frequency (1-50 kHz) SAS uses a combination of imaging and structural acoustics to detect and classify UXO. The sensors, signal processing, classification algorithms, and platforms requirements are in the early stages of development with regard to UXO remediation. SERDP should continue development of these types of sensors, systems, and associated platforms.

Previous side-bar meetings associated with magnetic, electromagnetic, and acoustic methods for detection and classification of underwater UXO suggest that sensor development should precede system and platform development and demonstration, especially those platforms with combined modalities. That is especially true for the lower frequency acoustic systems. Systems or platforms designed for mine clearance may not be appropriate for UXO remediation. Acoustic sensors, systems, and platforms should be optimized for UXO remediation across the full spectrum of UXO types, sites and environments. It is doubtful that a single acoustic sensor type or platform type is appropriate for all UXO types, sites or, environments. High-frequency towed or hull-mounted acoustic systems such as side-scan or multibeam sonar may be ideal for wide area surveys of UXO found proud on coral reefs or other hard bottoms; whereas a lower-frequency SAS mounted on an AUV or towed vehicle may be needed for detection of UXO buried in mud or sand. Many acoustic systems may not be appropriate for water depths shallower than 3 m, where issues associated with multipath, narrow beam widths, navigation and positioning with waves and currents may limit performance. In these shallow depths magnetic and EMI systems that crawl or are towed across the bottom may be more effective.

8.0 OTHER ENABLING TECHNOLOGIES

In addition to sensor systems, of which the acoustic sensors which were the subject of this workshop are one example, several other technologies will be required for an underwater munitions response. As discussed above, acoustic sensors can be mounted below the hull of boats, on autonomous or remotely-operated vehicles, or towed behind either. Geophysical sensors are more susceptible to metallic interference so the hull-mount option is likely not appropriate for these sensors. As the capabilities and limitations of each class of sensor are better defined, SERDP will be devoting an increasing fraction of its budget to deployment issues such as these.

For any sensor modality, analysis algorithms are required to enable detection of UXO and discrimination of the targets of interest from clutter and fragments. These algorithms may be based on a single sensor modality or, as we progress in our understanding of the individual sensors, a combination of sensor modalities each of which brings its own strengths to the job. The ultimate goal is to achieve a probability of detection and correct classification of 1.0 while minimizing the number of clutter items and munitions fragments classified as UXO.

Modeling capabilities for munitions migration and burial will be an important component of munitions response. Having a good estimate of the fraction of UXO that are proud versus buried will allow site managers to use imaging methods (acoustic or optical) to quickly estimate the extent of contamination at a site. These same models will allow the site manager to determine if another survey or a remedial action is required after extreme weather events at the site.

In a remedial action, the detected UXO must be removed from the site or treated. In some environments, this can be accomplished simply by blowing the UXO in place using an auxiliary charge attached to the item by divers. In other, more sensitive environments, intentional detonations would cause unacceptable harm to nearby flora and fauna and other methods will be required. If the UXO specialists conducting the remediation judge that the UXO is safe to move, it can be moved to the beach or a nearby barge for disposal. If not, methods to render the object safe by removing the explosive potential in an environmentally-benign manner are required.

Finally, every underwater munitions response action is likely to make use of mission planning software. Each site will have its own unique environmental conditions that will influence the choice of sensor or sensors and deployment methods. The clutter to be encountered will have some commonality among sites but will also include site-specific items such as crab pots in coastal bays and rivers and coral outcroppings in sub-tropical waters. High-quality mission planning software can guide the site manager through the decision required to identify an effective detection, classification, and, if required, removal scenario.

9.0 ACOUSTIC DATA SETS AVAILABLE

Recent field and laboratory acoustic experiments have developed a significant number of well-characterized acoustic responses from both free-field, proud and buried UXO. Most, if not all, the sediments were fine to medium sand. Data were collected at lower frequencies (1-50 kHz) and include multiple target aspect angles. These data together with FEM simulations provide the beginnings of a lower-frequency UXO acoustics library. As additional data sets become available, this list will be updated.

For access to these data, please contact the SERDP Program Manager for Munitions Response (571-372-6400, mr@serdp-estcp.org).

A subset of PONDEX09 and PONDEX10 data have been made available by NSWC, PCD.

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APPENDIX A: FINAL AGENDA

SERDP/ONR Workshop on Acoustic Detection and Classification of UXO in the Underwater Environment – July 16 and 17, 2013

Fort Myer
214 McNair Rd, Building 407
Joint Base Myer-Henderson Hall
Arlington, VA 22211

Tuesday July 16, 2013

0800	Name Badge Pick-Up and Morning Networking Session	
0830	Introduction to Workshop and Objectives	Anne Andrews, SERDP
0840	Introduction of Participants	Mike Richardson, SERDP/IDA
0850	Presentation: SERDP/ESTCP Support for Land-Based UXO Remediation	Herb Nelson, SERDP
0910	Presentation: SERDP's Past and Present Underwater Munitions Response Program	Mike Richardson, SERDP/IDA
0930	Presentation: ONR's Acoustic Mine Detection and Classification Efforts and Summary of ONR's iSSAM Workshop	Kyle Becker, ONR
1000	Break	
1020	Presentation: Navy Underwater Munitions Response Sites Overview	Bryan Harre, NAVFAC
1040	Presentation: Use of MCM Sensors for UXO Detection and Classification	Steve Hurff, NAVFAC
1100	Presentation: High-Frequency Acoustic Detection and Classification of Underwater UXO – State-of-the-Art, Research Needs, and Future Possibilities	Dan Sternlicht, NSWC-PD
1130	Presentation: Low-Frequency Acoustic Detection and Classification of Underwater UXO – State-of-the-Art, Research Needs, and Future Possibilities	Kevin Williams, APL-UW
1200	Lunch	
1300	General Group Discussion: Goals and Structure of the Workshop	
1330	Breakout Group Sessions	
	Group 1: State-of-the-Art for High-Frequency Acoustic Detection and Classification of Underwater UXO and Assessment of the Progress of SERDP's Acoustics Program	Group 2: State-of-the-Art for Low-Frequency Acoustic Detection and Classification of Underwater UXO and Assessment of the Progress of SERDP's Acoustics Program
1600	General Discussion Based on Breakout Group Reports	
1700	Adjourn for the day	

Wednesday July 17, 2013

0800 Morning Networking Session

0830 Reflection on the first day

0900 General Group Discussion: Requirements for Acoustic Detection and Classification of UXO. Development of a Set of Operational Metrics and Concepts of Operations for Underwater UXO Remediation

1000 Breakout Group Sessions

Group 1: Acoustic Detection   Group 2: Acoustic Classification

1. What are the limitations of acoustic systems given the performance metrics and operational scenarios?
2. What level of performance can be expected in different environments and for different types of munitions?
3. How much will clutter or noise degrade sensor performance?
4. Are robust target discriminators possible for all types of UXO and in all environments?
5. How does the environment affect sonar performance and what environmental factors are the most critical to understand and predict performance?

1130 General Group Discussion: Limitations of Current Systems Given Operating Environments and UXO Characteristics

1230 Lunch

1300 General Group Discussion: The Way Ahead

1. What are the optimal configurations for sonar hardware, platforms, and signal processing?
2. Are these systems available commercially, can they be adapted from evolving MCM systems, or are new systems required that are developed from the ground up?
3. How do we maximize performance of these acoustic systems?
4. What are the recommendations for future SERDP projects and ESTCP demonstrations?

1500 Final Comments and Direction for Workshop Report

1600 Adjourn

APPENDIX B: LIST OF ATTENDEES

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APPENDIX C: SERDP SIDE BAR MEETING ON UNDERWATER UXO: ACOUSTICS DISCUSSIONS AND RECOMMENDATIONS (DECEMBER 2, 2010)

Overview

The goal presented to the acoustics group, at least as we interpreted it, was: (1) to assess the present status of SERDP acoustics efforts relative to the vision put forth in the 2007 workshop; and given that assessment (2) to make recommendations on the way forward over the next several years.

This summary, which distills those discussions and presents recommendations, comprises three sections. Section I is mainly an extraction of relevant portions of the 2007 workshop report. Section II summarizes the current status of SERDP acoustics research relative to the recommendations in Section I. Section III presents recommendations for research directions over the next several years.

Section I: Initial recommendations from 2007 workshop

The two critical needs and recommendations within the 2007 workshop report that are especially relevant to the discussions of the acoustics group are reproduced here for convenience and labeled R1 and R2 for later reference:

R1. "Munitions detection capabilities of well established and emerging sonar and other acoustic systems need to be researched and documented. Characterizing the acoustic response of munitions in underwater environments is an essential first step. The signatures of munitions vary depending upon 1) munitions type and size, 2) if it is fully intact, distorted or broken into munitions-related scrap, 3) if it is filled or empty, and 4) if it is buried, partially buried or proud. Creating a signature library would be a useful tool to record this information, which would be particularly useful for structural acoustic techniques. A progressive range of research starting with modeling and basic tank tests with closely controlled variables was suggested. This would be followed by controlled open water data collections and real site demonstrations that would provide further insight as increasing site variables are introduced."

R2. "… detection of munitions on the seafloor would provide clear evidence that munitions activity occurred in the vicinity. The location of concentrated proud items can help guide site management decisions or plan future remedial investigations. There are several existing and emerging sensors that have the ability to detect proud items. These technologies have not been developed specifically for munitions detection and their performance in detecting proud and partially buried munitions needs to be verified through field demonstrations. Research should investigate a range of munitions and their associated sizes to assess current capabilities."

Section II: Current status relative to those recommendations

The group started with an initial discussion of where the SERDP program stands relative to R1. The presentations during this year's SERDP workshop showed considerable progress on this topic within the modeling and tank experiment arena. Thus the initial phase of R1 is well underway. Issues that remain regarding modeling and tank experiments in R1 include the impact on detection and identification of munitions' distortion and target burial. The latter includes both sediment loading effects and variations in target pitch angle. It was felt that in addition to resolving these issues to some extent, the next steps should involve controlled open water data collections.

As research has progressed relative to R1, it has become more evident that the probability of detection (Pd) requirements sought by SERDP (Pd very close or equal to 1 for buried UXO) preclude the type of large coverage rate, shallow angle detection (often called sub-critical angle detection), strategies sometimes used in the related Navy mine countermeasure (MCM) problem. Given this requirement, it is felt that as research moves to marine environments, short range, above critical angle detection strategies should be the primary area of focus, at least relative to the evolution of R1. (Further discussion below, relative to R2, incorporates shallow angle detection).

The group felt that, as the research effort moves to the field (ocean, bays, etc), it is important to develop a set of operational metrics and concepts of operation that can form a background for the engineering developments that will eventually transition to operational systems. Examples of topics where concrete metrics are needed include: burial depths for which targets need to be detected and variation of this metric with target size; what Pdc/Pfa values will be considered acceptable and how this might vary with site usage; and timeline requirements for detection/classification operations.

The group anticipates that the Pdc/Pfa metrics may eventually point to the need for systems that combine acoustics with other modalities such as passive magnetic or active electromagnetic systems. We feel, however, that each of these modalities should carry out research that quantifies/optimizes its capabilities separately as a precursor to integration of modalities.

Though the Pd's for R1 efforts involving buried UXO dictate steep angle strategies, the use of acoustics to detect proud UXO (applicable for both R1 and R2) implies less stringent requirements. Using the R1-focused low frequency sonars for addressing R2 motivates shallow angle (long range) examination of proud UXO with these sonars.

Also for R2, sidescan, sector scan and multi-beam sonars, which can work effectively on proud or partially buried targets, may allow evidence that munitions activity occurred in the vicinity. The group was not aware of demonstrations to this end; however there has been significant use of these types of sonars in preliminary environmental assessments in support of magnetics and electromagnetic demonstrations.

We feel there are gains to be made in further research using these types of high resolution sonars. This research should be field experiment/demonstration oriented. Particular areas of research that should be considered include the following: 1) assessing UXO mobility and burial using sector scan sonars, 2) using the traditional hundreds of KHz sonar systems to derive absolute acoustic scattering strength and invert for sediment material and interface properties, 3) using the new generation of sidescan and multibeam sonars that operate at Mega-Hertz (MHz) frequencies to image small, proud UXO during wide area surveys.

It is important to note that the Navy has ongoing efforts related to the MCM equivalent to R1 and R2. Continued coordination with those efforts where possible could be advantageous to both the MCM and UXO problems.

Section III: Recommendations going forward

Given our perception of the current status as presented in the previous section, our recommendations are that*:*

1. A set of operational metrics and concepts of operation should be developed as part of the SERDP program so that progress toward operational system(s) can be both motivated and monitored and design of these same systems can be carried out.

2. The experimental portion of UXO-related acoustic research related to R1 should focus on well-controlled shallow water field experiments. Here the principal issues involve characterization of munitions responses in these environments regarding types and sizes, physical condition, and burial condition as well as characterization of the nature of interfering clutter returns. Within this context we can see the utility of both short-term (one to two week) experiments focused on R1 and longer term (several week to several month) experiments that combine the research aimed at both R1 and acoustic monitoring in support of UXO mobility and burial.

3. Since it is a given that experiments cannot be carried out under all the environmental conditions that will be present during UXO operations, modeling efforts in support of the experimental program should be continued. The model results need to be compared to experimental results within the context of both target echo response and classifier learning. One goal would be the ability to assess system performance relative to Pdc/Pfa metrics.

4. Research should be carried out aimed at: a) deriving further environmental information from the acoustic systems used in support of magnetic and electromagnetic demonstrations, and b) using higher frequency versions of these same types of systems in wide area surveys for proud UXO.

5. In the long term, system strategies that combine modalities (acoustic, magnetic, electromagnetic) may be needed. However, in research and demonstrations to this end, the capabilities of each sensor type needs to be separately understood, optimized as a precursor to combining modalities. Doing so will allow quantitative assessments of improvement to Pdc/Pfa allowed by combining modalities (where it may not be possible to use each modality in its optimal configuration).

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